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AIR POLLUTION FROM AIRCRAFT

Semi-Annual Progress Report on

NASA GRANT NGR 22-009-378*

February 1975 - August 1975
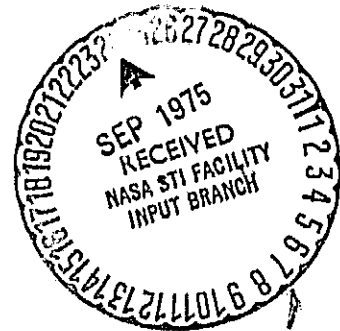
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1. BACKGROUND

This progress report reviews the current status of work conducted on NASA Grant NGR 22-009-378. The grant was initiated at MIT in 1969 to study the production and dispersion of pollutants from aircraft jet engines. In the course of the grant, a series of basic problems have been examined. Work completed at MIT includes an analysis of the soot formation and oxidation rates in gas turbine combustors, modelling the nitric oxide formation process in gas turbine combustors, a study of the mechanisms causing high carbon monoxide emissions from gas turbines at low power, an analysis of the module wake region and downstream mixing in the NASA swirl can combustor, and the dispersion of pollutants from aircraft both around large airports and from the wakes of subsonic and supersonic aircraft.

During the current grant period, work has been focused on the combustion and flow characteristics of the NASA swirl can modular combustor. At MIT, a model which predicts nitric oxide (NO) and carbon monoxide (CO) emissions from the swirl can combustor was completed during the previous reporting period, and experimental verification of major assumptions in the model has now been completed. These experiments included a detailed analysis of the turbulent fuel-air mixing process in the swirl can module wake region. These studies are all intended to provide basic information relevant to the NASA Clean Combustor Program in which similar combustor components are being developed. It is anticipated that these models will be used to assist in concept optimization, particularly in achieving

improved fuel-air mixing. In addition to this work at MIT, an extension to the program in July, 1973, was approved by NASA to support more detailed experimental studies of the swirl can module wake region in the Fuel Technology Laboratory at the University of Sheffield. This program complements and extends the MIT program, which is designed to determine the variation in overall module parameters (e.g., total air entrainment into the module wake, mixing rates downstream of the module wake) as operating conditions are changed. Results from the Sheffield program are providing important confirmation of theoretical estimates of fuel-air mixture uniformity and mixing rate intensities in the combustion zone, an important parameter in the analysis of NO_x and CO emission characteristics. In addition, the University of Sheffield program is providing substantial new information on the atomization and fuel distribution characteristics of the swirler in the current combustor design, on the detailed flow pattern in the module wake, and on the extent of spatial fuel-air ratio nonuniformities in the region where most of the NO_x emissions are formed.

2. PERSONNEL INVOLVED IN PROGRAM

The personnel currently active in this program are:

In the Mechanical Engineering Department at MIT

Professor John B. Heywood, Principal Investigator

Dr. Richard C. Flagan, Research Associate

Dr. R.E. Hicks, Visiting Research Associate

Thomas Mikus, Research Assistant

In the Department of Chemical Engineering and Fuel Technology, University
of Sheffield

Dr. Norman A. Chigier, Reader, Principal Investigator

Dr. Dennis Thompson, Post-Doctoral Research Fellow

A. Ungut, Research Assistant

R. Bennett, Part-time Research Assistant

3. WORK COMPLETED IN CURRENT REPORTING PERIOD AT MIT

3.1 Modelling Studies

3.1.1 Emissions Models

The models for predicting NO and CO emissions from the NASA swirl can
combustor developed on this program were summarized in the previous pro-
gram report. In the current reporting period, some additional calculations
of both NO and CO emissions as a function of overall combustor fuel-air
ratio have been made with model input parameters chosen to be consistent
with data obtained from the experimental program. Calculations of CO
emissions using either the assumption that CO concentrations are in
equilibrium, or that the CO combustion is constrained by the rates of the
three-body recombination reactions and the CO-OH oxidation reaction, indi-
cate that only for leaner overall fuel-air ratios is the CO chemistry
significantly frozen. The calculated CO emissions are higher than NASA
experimental combustor rig data. A possible cause of this discrepancy
may be that CO oxidation was not immediately frozen in the gas sampling
system.

Two papers describing these modelling studies are being prepared.

3.1.2 Droplet evaporation calculations

Because extensive flow visualization studies were being carried out with a cold flow rig, and with water to simulate the fuel, estimates have been made of characteristic droplet size and evaporation times. Shadow-graph photographs of water droplets emerging from the swirler (see 3.2.3 for a description of the apparatus used) were used to estimate approximate maximum droplet sizes as a function of reference velocity. Diameters (for water) of order several hundred μm were observed. These were consistent with estimates of maximum stable drop sizes.

A computer program which calculates droplet lifetimes of isolated droplets of pentane and kerosene evaporating under various combustor conditions was written. Since the temperature of the immediate environment of the evaporating droplet is not known, two limiting temperatures were used: the estimated primary zone adiabatic flame temperature, and the final mixed temperature at the combustor exit. Results for kerosene in a combustor opera-ting with air supplied at conditions covering the range expected from idle and cruise showed that fuel entering the combustion region is always vaporized in a distance which is less than 7 percent of the blockage plate diameter (d). Some fuel, however, is entrained in the secondary air flow (see section 3.2.3). At idle conditions, the temperature of the secondary air is initially 482°K, and calculations show that only 60 percent of the fuel entrained in air at this temperature would evaporate in a distance of 2d.

Calculations for pentane in a combustor operating with air supplied
at ambient conditions showed that 99 percent of the fuel is evaporated
by 0.4d and 2.3d downstream at idle, and 0.2d and 1.1d at take-off,
for the environment at the primary zone adiabatic flame temperature
or at the combustor exit temperature, respectively. It was concluded
that kerosene at real combustor conditions has characteristic evaporation
times shorter than pentane at atmospheric ambient air conditions. Visu-
alization experiments with pentane and propane were therefore carried out
to bracket the range of evaporation times expected for kerosene at engine
operating conditions.

3.2 Experimental Studies

3.2.1 Experimental Set-Up

A flow rig for tests on a single swirl can module had been set up
during the previous reporting period. The rig is coupled to a laboratory
air compressor capable of delivering 0.4 lb_m/sec at atmospheric pressure
and temperature. The test section simulates an average module in the
NASA annular swirl can combustor. The single module with a circular
blockage plate of 2.23" diameter is mounted in a 2.57" ID tube which
diverges to a 2.83" ID tube to simulate the cross-sectional area change
of the annular combustor downstream of the blockage plate. Cold flow
experiments, with a hydrocarbon tracer introduced behind the swirler
on the module axis, had been initiated, but difficulties in obtaining
axisymmetric tracer distribution had been experienced. A plexiglass
swirl can module for flow visualization studies had also been constructed
during the previous reporting period.

3.2.2 Cold flow tracer experiments

The cold flow tracer experiments were designed to follow the swirler airflow as it mixes with air which flows around the blockage plate. The difficulties experienced with nonaxisymmetric tracer concentration profiles downstream of the blockage plate was due to inadequate mixing between tracer and swirler airflow upstream of the swirler. A 6 inch long lead-in tube was fitted to the upstream end of the module can, and the tracer was injected at the upstream end of the tube. Essentially uniform distribution across the can diameter just upstream of the swirler was obtained by this means.

Cold flow concentration contours were then obtained by injecting propane into the upstream can flow as described above, and determining hydrocarbon concentrations at downstream locations using a sampling probe on a micrometer traversing mechanism and a flame ionization detector. Due to the steep concentration gradients within the downstream flow, gas samples were withdrawn at points on a 0.050" x 0.100" grid at several axial locations.

The tracer gas analysis showed that the can flow is diluted about 6.8 times on mixing with the by-pass flow; i.e., about 15 percent of the total air flow passes through the swirler. As the vane open area is about 21 percent of the total open area, mean velocities through the gap and the vanes are similar.

An available computer routine was used to process the point concentration data and produce contour maps for one quadrant of the flow

field. The contour maps showed a central recirculation zone of essen-
tially uniform composition (with a tracer concentration equal to the
uniformly mixed value well downstream) surrounded by an annular region
where the individual jet structure, and higher tracer concentrations,
could be discerned (at least close to the blockage plate). This annular
region of high tracer concentration in turn is surrounded by a mixing
·region where tracer concentrations decreased rapidly; and finally the
outer annular flow is air which by-passes the mixing and recirculation
zone. The outward motion and radial diffusion of the jets is clearly
illustrated. The jets are not assimilated into the recirculating flow
but maintain their identity and "blow away" the outer portion of the
wake.

Close to the blockage plate there is a second well mixed region
which lies directly behind the plate, and extends only a short distance
downstream. This region is thought to provide appropriate conditions
for flame stabilization.

3.2.3 Flow visualization studies

For flow visualization experiments, with both cold flow and hot
flow (with combustion of a hydrocarbon fuel), a plexiglass upstream
pipe section and can body were used with a metal swirler and annular blockage
plate. Use of a downstream pipe section proved to be impractical for
this work since it blocked the field of view, so the can was mounted
flush with a plexiglass flange at the end of the upstream pipe section.

In the visualization experiments, smoke, neutrally buoyant helium filled soap bubbles, and a liquid fuel (water or pentane) were used to trace the gas and liquid droplet pathlines. Time exposure and strobe photographs (2-3 μsec exposure), shadowgraphs, and high speed movies (4000 frames/ sec) were the techniques used.

The presence of the recirculating wake and some of its characteristics were illustrated by the pathlines traced out by the helium soap bubbles. The size of the wake was determined by probing with a wool tuft. It was found to be ≃ 1.0d in the case of an unconfined downstream flow, and to lengthen to 1.8d when the downstream pipe was placed in position.

The spatial and temporal uniformity of the fuel-air ratio resulting from the fuel injection system of the swirl can model studied was not good. Inspection through the plexiglass can body revealed that the jet of fuel emerging from the supply line forms a puddle on the hub of the swirl plate which in turn feeds fuel to the swirl vanes. Although the jet impinges centrally, the puddle, which is slightly smaller than the hub diameter, is generally displaced to one side, and supplies fuel only to those vanes with which it makes contact. Attempts to obtain a more uniform fuel distribution by displacing the fuel jet were not success- ful. Rivulets of fuel are drawn off from the puddle onto the downstream face of the swirl vanes, whence they are entrained into the flow by two possible routes. In some cases the fuel stream detaches immediately from

the vane surface and is carried downstream in the primary air jets.
In other cases, the fuel rivulets flow diagonally across the face of the
vane and onto the blockage plate where it spirals outward. This fuel
is entrained directly into the by-pass air flow.

High speed movies showed that much of the fuel leaves the swirl
can in a series of spurts. The duration of these spurts is of the order
of milliseconds, while the interval between spurts is of the order of
tens of milliseconds. It follows that the fuel-air ratio can reach
values several times that calculated on the basis of steady fuel flow
rates.

Shadowgraph photographs were taken to determine droplet size ranges
using water to simulate fuel. The maximum droplet size was found to
decrease significantly with increasing reference velocity. Initial
drop sizes close to the swirler were large (e.g., at 20 m/s reference
velocity, $\simeq$ 500 μm). Subsequent atomization in the high shear flow at
the edge of the blockage plate reduced these maximum droplet diameters
by a factor of about four.

3.2.4 Hot flow experiments

Flame photographs were taken with both propane and pentane fuels.
Both fuels burned with a blue flame that formed an envelope surrounding
the recirculation wake region. The flame was attached to, and apparently
stabilized by the blockage plate. When burning pentane, a secondary
orange/yellow unsteady flame could be seen inside, but separated from,

the main blue flame. Since flame lengths (> 1d) are substantially longer than the distance required to evaporate the larger size drops emerging from the swirler, it is concluded that droplet evaporation is probably not the rate controlling factor in the burning process.

With propane as fuel, a series of species concentration profiles at different axial stations were measured in the rig with the single module mounted inside a confining cylinder of appropriate ID for the NASA swirl can annular combustor data (see Section 3.2.1). CO_2, CO, O_2, HC and NO_x concentrations were determined through gas sampling and analysis. For these measurements, the fuel-air equivalence ratio at each measurement position was determined. Measurements of this type were not made with pentane because a portion of the fuel collected on the containing cylinder duct walls, flowed downstream along the walls, and burned at the exit plane of the cylinder where the flow "dumped" into an exhaust section.

Equivalence ratio contours were determined in a manner similar to that used to develop the contours for the cold flow tracer experiments. Qualitatively, the equivalence ratio and tracer concentration maps were similar; however, the uniform recirculation zone in the hot flow tests had an equivalence ratio 1.5 to 2 times the overall value as compared to cold flow tracer concentrations roughly equal to the overall concentration. The individual jets were not as clearly defined in the hot flow experiments as in the cold flow, though they were identifiable up to about 1/2 diameter downstream of the blockage plate.

A rough evaluation of the average fuel-air equivalence ratio in the primary combustion zone (recirculation zone and outer mixing region) from these hot flow experiments indicates that the value, of 2.5 times the overall combustor fuel-air equivalence ratio obtained previously by matching NO_x emissions data with computer model predictions is approximately correct.

A paper describing the results of the experimental program is being prepared.

4.1   Aerodynamic Investigations of 6-module Array

In addition to the investigations of a 6-module array by pitot tube and hot wire anemometry, using a wind tunnel with a calming chamber and contraction nozzle assembly, a further investigation using a wind tunnel, in which flow through the cans has been visualized by smoke seeding, has been carried out.   The output of the wind tunnel was continuously variable from zero to 30,000 cu ft hr^{-1}.   A rectangular section of the same internal dimensions as a 6-module cluster spaced in accordance with the dimensions used in NASA full annular tests, led to a plexiglass text section.   Smoke was introduced locally immediately upstream of the can array, and the patterns so produced were photographed downstream of the exit plane of the array.

The photographs clearly showed separate flows associated with individual slits in the swirler and contra swirler, and the presence of reverse flow regions downstream of the swirler hub and the solid

annulus between the swirler and contra swirler slit annuli. Gross
inflow of gas towards the axes of the modules, with associated large
scale vortices were observed to be present a few can diameters down-
stream of the exit plane. The type of flow is in accordance with flow
patterns previously observed downstream of bluff bodies.

A program of hot wire anemometry investigations previously re-
ported to be underway has now been completed and a report on the inves-
tigation has been submitted and discussed in detail with NASA personnel
by Dr. Chigier. The instrumentation has been transferred to a combus-
tion test rig, and results are being obtained which will allow us to
compare the combustion test conditions with those which occur in a full-
annular can-array, as represented by the 6-module array.

It has been found that 18% of the flow passes through the combustor
cans, and the remaining 82% is bypass air. 7% of the air passes through
the inner swirler and 11% passes through the outer swirler (contra-
swirler). Turbulence levels downstream of the inner swirler were high,
and it is possible that this turbulence arises from aerodynamic inter-
ference by the can body inlet lip, and because of the significant thick-
ness of the swirler blades by comparison with the size of the slit
apertures, so that the blades and lip act as bluff bodies and shed
vortices. Boundary layers of significant thickness surround the contra-
swirler shroud, so that the bypass airflow must be regarded as closely
associated with that through the cans. The flow pattern in the regions
where can swirler shrouds are close together and the flow is the result

of interaction between two cans must be regarded as occupying a signifi-
cantly extensive region. The results indicated the presence of the reverse
flow regions directly observed by smoke visualization tests. Discrete
flow maxima were observed over each of the swirler and contra-swirler
slit exit, and this clearly indicates that the flow downstream of the
can will not have the characteristics of swirl stabilized flames
characteristic of normal indus..ial swirl-stabilization practice -- i.e.,
the flame will have structures in the stabilization zone which may be
associated with individual slits. This has been confirmed by preliminary
observations of a flame stabilized on a single combustor can.

4.2 Combustion Investigations: The Air Supply System

The system to supply preheated air (up to 500 K) at up to 600 cfm
and 100 psi has now been fully instrumented and tested. A dual
gaseous and liquid fuel supply system has been installed, and will
allow investigations of the effect of fuel inlet pressure at up to
cylinder pressure in the case of gaseous fuels and at up to 300 psi
for liquid fuels. At present, a single fuel inlet nozzle immediately
upstream of the combustor can swirler is used.

Hot wire anemometry investigations of the flow through the con-
traction nozzle system, in order to establish the extent of boundary layers
at the walls are now underway. These investigations are also being
extended to study flow patterns downstream of a combustor can mounted
in the exit of the contraction nozzle assembly. These results are to be

retained as necessary information for correlation of combustion data with the expected flow patterns in full annular combustion investigations, as represented in our investigation by the 6-module can-array.

Preliminary combustion tests have been carried out. Propane was used as fuel. The tests have indicated that by adjustment of relative airflow through the inner and outer air-supply contraction nozzles, and fuel input, a very wide range of flame characteristics may be obtained. These range from a luminous-recirculation core with high fuel throughput and an open-ended blue flame, with low throughput. The form of the flame changed significantly with a change in the ratio of flow impacted on the combustor from the outer and inner contraction nozzles. Under intense blue flame combustion conditions, discrete flamelet structures downstream survived as entities sufficiently far downstream for reversal of their radial direction on interaction with flow through the outer swirler to be clearly visible. These observations are in agreement with conclusions from cold-flow investigations, i.e., the combustor cannot be regarded as comparable to an industrial-type furnace swirl-stabilized flame. At the same time, it is good evidence that for the purposes of investigation of this type of combustor, the highly flexible 'zero perturbation' approach flow conditions have been attained. It will thus be possible to carry out the investigation under these conditions, and to introduce perturbations due to known bodies upstream of the cans to simulate their use in a gas turbine with associated equipment present.

Initial characterization of this flame is now underway; the results
will be used to select the test conditions for detailed investigation to
provide the most valuable information.

4.3 Combustion Investigations; The Sampling Systems

4.3.1 Non-instrusive Techniques

A laser-Doppler velocity measurement system is currently in use
by Mr. Ungut, in an investigation of particulate size vs. scattered-
light interference-fringe intensity, wave envelope and frequency relation-
ships. Investigations in this Department have shown that clear laser-
Doppler signals may be obtained from larger particles than current theory
predicts. The relationship between the form and intensity of such
signals, and the reasons for their occurrence at all must clearly be
determined for application of the laser-Doppler technique to flames
burning liquid fuel, where droplets may be expected to be present in the
stablization region. There are both positive and negative reasons for
this: it is desirable to be able to eliminate signals due to large drop-
lets from analysis of data when determining the gas flow velocity, and
to consider only the signals due to small seeding particles, since the
trajectories of large droplets will differ significantly from the flow
streamlines due to their high inertia. At the same time, knowledge of
the trajectories of the droplets themselves would be a valuable aid to
flame structure interpretation.

A theoretical investigation has indicated that the failure to
predict the observed fringes on the basis of existing theory may be due

to failure of the approximate mathematical treatment involved to take into account geometrical factors which occur in the full (insoluble) scattering equations, and which become significant for large droplets and particles. A modified approximate equation has been developed, and there is encouraging agreement between the form of interference signal predicted and the form of signals observed experimentally for large droplets. The investigation has also shown the potential for use of the intensity of the signal, hitherto neglected, as a source of further information about particle size distribution and velocities.

The information obtained in this investigation will be used in the analysis of data obtained from combustion tests on a NASA swirl-can mounted on an air supply system identical to that already established, and using the same flow control and preheat system. The combustor will be mounted in a laser-Doppler system which is already established and used to investigate a liquid fuel flame; preparation of equipment for minor modifications necessary to the system is underway and the modifications will be carried out over a short period when the equipment becomes available in the near future.

4.3.2 Probe Sampling Techniques

A system for measurement of high frequency temperature fluctuations by the compensated thermocouple technique has been assembled and tested. The unit uses fine-wire Pt/Pt-13%Rh thermocouples 0.003 - 0.005" dia where possible, in order to minimize flame disturbance. During investigations with preheat it is anticipated that temperatures above the operating

temperature of these thermocouples will be attained, and the range will be extended by the use of Ir/Ir-40% elements. The compensated thermocouple technique allows measurement of temperature fluctuations in the frequency range up to several thousand Hz. Dr. Thompson has utilized the technique and carried out theoretical investigations of its validity in the past.

A comprehensive microprobe sampling and analytical unit has been constructed, and tested unit-by-unit, and the system is currently being assembled, and full routine overhaul of the component units carried out so that run-time failure due to breakdown will be minimized. The unit consists of: a fine quartz microprobe, through which gas samples are withdrawn from the flame; the pressure inside the microprobe is maintained at only a few tens of mm Hg, so that flow through an orifice at the tip is sonic. Reactions of chemical species in the sample are quenched both by the sudden cooling which results from expansion, and the very large reduction in reaction rate due to the drop in pressure, since the rate of the majority of gas phase reactions is proportional to the square of the total pressure. The probe is pumped by a large rotary vacuum pump. A Cartesian diver-controlled pressure regulator maintains a constant pressure at the probe in the presence of drift in the working rate of the pump or variation in gas flow rate through the orifice due to changes in gas composition, so that a fixed reference state is obtained. Samples are withdrawn from the probe-to-pump line, to supply a gas chromatography unit, a mass spectrometer, a nitric oxide analyzer, and, potentially, a HCN detection train, if the role of the latter in nitric

oxide formation via the 'prompt-NO' route is found to have significance in the present investigation. The gas chromatograph is a twin-column automatic sampling unit developed in part in this Department, in collaboration with British Steel. Analyses are obtained every four minutes, and CO, CO_2, H_2, O_2 and N_2 concentrations are measured. It is necessary that the sample is supplied to the gas chromatogram at above atmospheric pressure, and this is achieved by compression of the low pressure sample initially obtained with a medical-grade contamination-free two-stage peristaltic pump. The mass spectrometer is an AEI MS2 90° sector instrument with double collector slit and a 'peak-dwell' scan and recording system which gives it ideal characteristics for accurate analyses of the type of sample which it is expected will be obtained. The sample pressure is reduced to the necessary level for admission to the ion source by the gas handling system of the spectrometer itself. A wide range of operating modes is available, and the instrument will be used not only for routine batch analyses, but for rapid continuous peak traverses at fixed m/e for several species. Where unburned hydrocarbon mixtures are obtained in the flame stabilization zone the system will be used to store and study more closely the more complex mixtures. A third bleed provides samples for nitric oxide analysis. A Thermoelectron Corp. commercial instrument is currently available. A unit based on typical chemical laboratory practice is currently under construction and will be installed permanently in the sampling system when complete.

It is considered that this sampling system will have a cycle time of approximately 5 min, which represents an ideal balance between a

long sampling interval to assist operator checks of test conditions and data quality, and a short sampling interval to minimize run-time failure and multi-day runs, with associated problems of reestablishment of exact replicate conditions and high running costs.

A theoretical investigation is currently underway. In this investigation attempts are being made to unify the specific approaches to the problem of nitric oxide formation in flames of chemical kinetic investigations, practical flame experimental investigations, chemical engineering reactor appraoch, and modern aerodynamic concepts and flame structure concepts to obtain an approach which removes the inappropriate assumptions of each topic whilst providing a model suitable for application to typical flames without unduly high computer time requirement.